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Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report results from a contract tasking Crystal Fibre A/S as follows: Crystal Fibre A/S will develop a taper/coupler solution to interface between a new polarization maintaining/polarizing amplifier fiber (DC-200-35-Yb-PM) and respectively pump fibers and a signal input fiber. The anticipated intermediate interface will be a 250 micron/0.46 NA pump guide and 20 micron MFD PM signal core fiber. We will seek to further interface this fiber to a tapered fiber bundle with either 100 or 200 micron pump fibers and a polarization maintaining signal input fiber. It is the goal to achieve an interface with 6 multi-mode pump input ports consisting of 200/220 0.22 NA fiber with a polarization maintaining 20 micron core signal feed through capable of single-mode operation at 1064nm. In case this is not possible, a fallback solution will be 6 (or more) multi-mode pump input ports consisting of 105/125 0.15 (or 0.22) NA fiber with a polarization maintaining 7 micron core signal feed through capable of single-mode operation at 1064nm. Two fiber amplifier sub-assemblies including the developed components and an appopropriate length of active fiber (3-4 m) will be delivered at the end of the project.

15. SUBJECT TERMS
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GENERAL

Government Purpose Rights	
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Recipient's Name:	Crystal Fibre A/S
Recipient's Address:	Blokken 84, DK-3460 Birkerød Denmark
Date:	December 2005
Customer organization:	Air Force Research Laboratory, AFRL/Kirtland
Customer contact:	Capt. Benjamin G. Ward
Project Manager:	Martin Dybendal Nielsen (mdn@crystal-fibre.com)
Report By:	Martin Dybendal Nielsen (mdn@crystal-fibre.com)
Device:	7 port Air-clad pump combiner

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SHORT DESCRIPTION

The focus of the work described in this report is the development of a multi-mode (MM) pump combiner with a high NA air-clad output. The input side of the combiner is 7 individual MM pump delivery solid all-glass fibers. The NA of the MM input fibers have an industry standard value of 0.22.

The combiner is intended to consist of a fused fiber bundle interfaced to an air-clad PCF. The PCF is tapered to increase the NA. The device is shown schematically in Figure 1below.

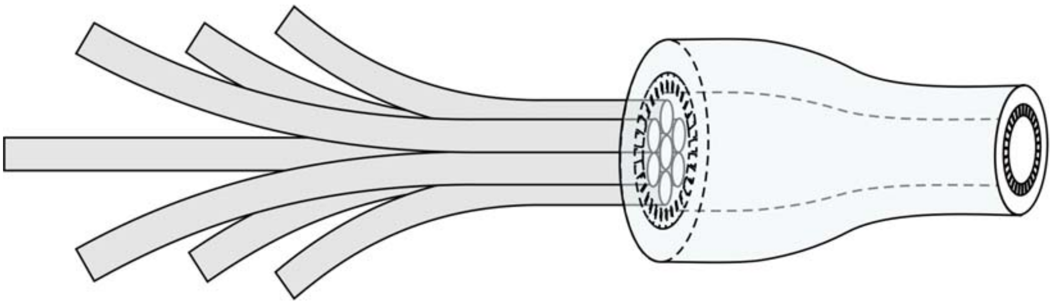

Figure 1 *Schematic drawing of the 7 port pump combiner.*

MOTIVATION

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In a typical standard fused fiber coupler a number of all-glass 0.22 NA pump fibers are bundled, fused, tapered and spliced to a high NA polymeric clad 0.46 NA output fiber. The taper and splice are packaged in a sealed device, typically a steel tube.

A central advantage of the air-clad photonic crystal fiber is the high numerical aperture which can be obtained, typically around 0.60, resulting in correspondingly small pump guide diameters, high pump absorption rates, short fiber length, and thereby suppression of non-linear effects.

For the realization of monolithically integrated all-fiber lasers fused fiber couplers are important components. However, due to the limited 0.46 NA of standard couplers these will typically be problematic to use in context with PCF since the full NA of the pump guide cannot be utilized or because the inner cladding of the fiber will be too small to couple in the light with good efficiency.

For these reasons, an all-fiber based combiner with a high NA air-clad output is desirable.

FUSED BUNDLE SECTION

The input pump fibers used in this development have a cladding diameter of 125 µm and a core diameter of 105 µm. The NA of 0.22 is provided by an F-doped cladding layer.

The chosen approach is to obtain a fused bundle where the light is still guided in a 0.22 NA supported by the F-doped claddings. This has the advantage that light will not be guided in a glass/air interface anywhere in the coupler. In order to realize such a bundle, the fusing should take place without any tapering of the bundle. Also, the transition from individual fibers to a fused bundle should be an adiabatic transition. Finally, the fused bundle should have a round shape in order to match the geometry of the air-clad PCF and thereby allow for the lowest possible loss of brightness.

The bundle fabrication was made using a Large Diameter Splicer (LDS-1250) manufactured and commercially available from Vytan (www.vytran.com). The fusing is performed by placing 7 uncoated fibers in a capillary tube with an inner diameter of 385-400µm corresponding to 3 times the fiber diameter plus a small gap. This approach ensures that the fibers are positioned in a close-packed arrangement and do not cross in any way.

For the initial development of the fused bundle technique standard, SMF-28 fiber was used. In Figure 2, a cross-section of a fused SMF-28 fiber bundle is shown. The sample is illuminated from the back clearly showing the position of the 7 cores of the individual fibers. From the image it was deduced that the fusing did occur without any tapering.

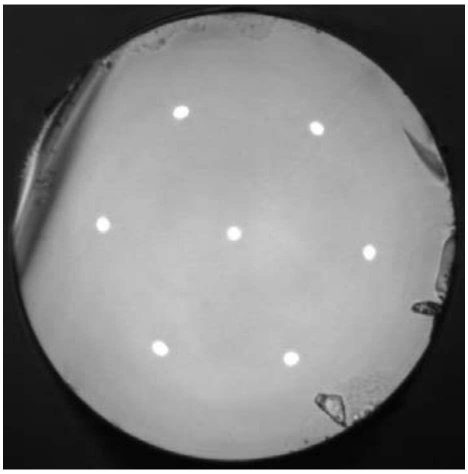


Figure 2 *Cross-section of a fused fiber bundle made from 7 close-packed 125 µm cladding diameter standard SMF28 fibers. The bundle is illuminated from below to show the 7 individual cores.*

In Figure 3, a cross-section image of a fused fiber bundle made from 7 standard 105/125 0.22 NA multimode fibers is shown. The low-index cladding of each of the fibers is observed as the dark areas. The diameter of the bundle shown in Figure 3 is ~380µm.

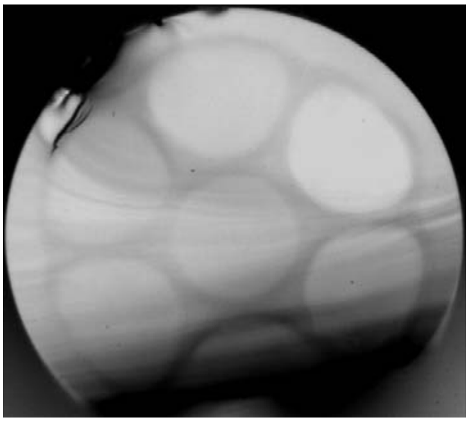


Figure 3 *Cross-section of a fused fiber bundle made from 7 close-packed 125 µm standard 105/125 0.22 NA multimode fibers. The 7 individual cores are clearly visible.*

TAPER SECTION

In the fused un-tapered fiber bundle, the NA of the pump light is the same as in NA of each of the individual fibers prior to fusing.

In the following step of the combiner the bundle is spliced onto an air-clad PCF with an inner cladding equal to (or larger than) the diameter of the fused bundle (see Figure 1). The device now combines the 7 individual 105/125 0.22 NA fibers into a single multimode air-clad PCF but still with the low NA of the pump and therefore in a relative large pump guide diameter.
In the following step, the PCF is tapered down in order to increase the NA and decrease the pump guide diameter. The NA of the light is increased by the factor of diameter reduction due to the brightness conservation. This up-conversion of the NA can be performed without loss of light provided that the NA of the PCF supports the full NA of the light at any give point along the taper.

For the air-clad PCF, the supported NA is predominantly determined by the width, Δ, of the silica bridges connecting the pump guide to the outer cladding of the fiber relative to the optical wavelength, λ. As the bridge width is decreased, the supported NA increases. When the air-clad PCF is tapered down the width

of the silica bridges are reduced by the same factor as the fiber diameter. The supported NA of the fiber will therefore increase as the fiber is reduced in diameter.

In Figure 4, a theoretical relation between the supported NA and the bridge width relative to the optical wavelength is shown. The curve is calculated from the difference in refractive index between the core region and the microstructured region (cladding region). The effective index of the microstructured region is calculated by modeling the structure as an infinitely long isolated silica strand in air (slab waveguide model). Despite the simplicity of the model the agreement with measurements is overall excellent as long as the length of the silica bridges are in the order of a few times the optical wavelength or more.

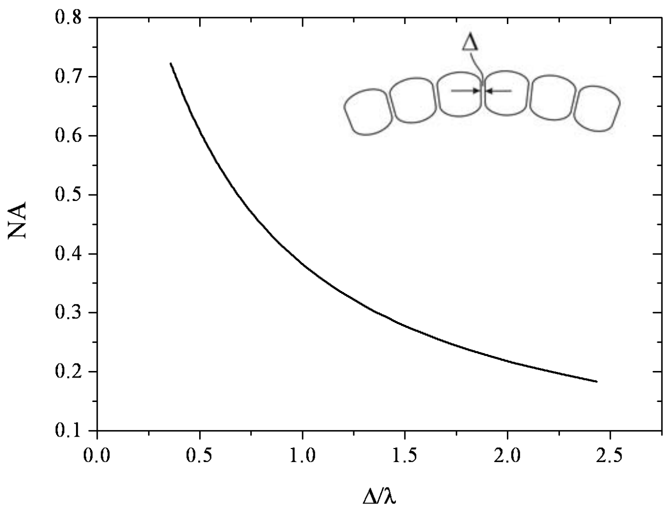
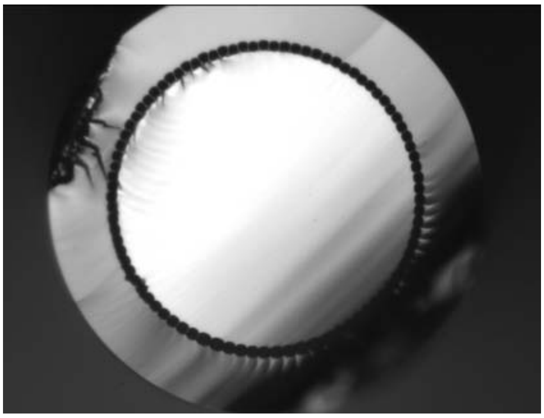


Figure 4 *The curve shows the theoretical relation between the supported NA of the air-clad and the bridge width relative to the optical wavelength. The insert indicates the bridge width of a typical air-clad geometry.*

The non-linear dependency of the NA on Δ implies that the NA of the un-tapered PCF should not just support the 0.22 NA of the input fibers. In that case the NA of the light will become larger than the supported NA of the fiber as soon as tapering occurs. Aiming for and output NA of 0.60 the tapering ratio should be $0.60/0.22 \approx 2.7$. Since this would also be the reduction factor for Δ, the supported NA of the un-tapered fiber should, according to Figure 4, be around 0.35.

In Figure 5, facet images of the un-tapered and tapered air-clad PCF are shown. In the un-tapered case, the pump guide diameter is 405 µm while the tapered end has a corresponding dimension of 148 µm.



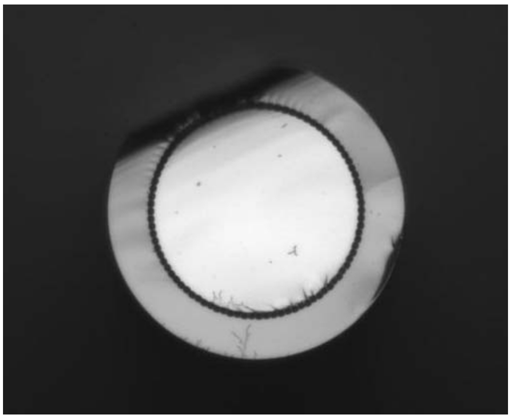


Figure 5 *Facet images of the un-tapered (left) and tapered (right) air-clad PCF. Inner cladding diameter of un-tapered fiber is 405µm while the tapered end has an inner cladding of 148µm. (NOTE: images are not to same scale).*

In Figure 6, the measured far-field distribution of multimode light launched on the input and measured at the output of the tapered air clad fiber is shown. Defining the NA as sine half the FWHM, angle the measurements show that the taper converts an input NA of 0.22 to an output NA of 0.60.

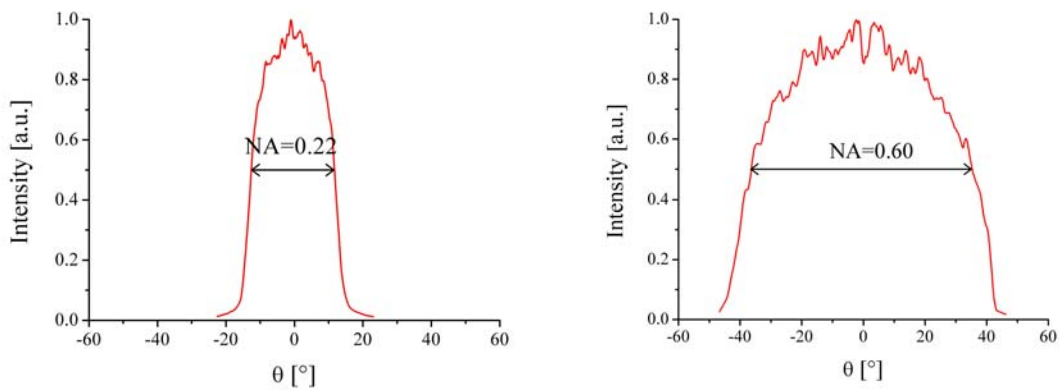


Figure 6 *The curve to the left shows the measured far-field distribution of multimode light launched at the input side of the fiber taper. The curve to the right shows the corresponding measured far-field distribution on the output side of the taper. The FWHM NA values are extracted and shown on both curves.*

The pump guide diameter is tapered from 405µm to 148µm corresponding to a theoretical output NA of 0.22*405µm/148µm = 0.602 which is in perfect agreement with the measurements. Since the measured output NA scales directly with the pump guide diameter there can be no mode-coupling to higher NA components taking place in the taper. Provided that no power is lost, the taper can therefore be concluded to conserve the brightness of the light at the input.

The length of the tapering section can be made short as in the order of a few millimetres. In Figure 7, a side-view image of the tapered air-clad PCF is shown. Lengths of 3mm, 5mm, and 10mm were tested all showing good transmission. 5 mm was chosen as a preferred length in order to keep the taper as short as possible while taking into consideration the mechanical stability. The cross-section area of the fiber is reduced by more than a factor of 7 and doing this over only 3 mm made the taper neck weak due to the stress increasing factor. Also, a 5 mm length is sufficiently short not to be a decisive parameter for the length of the complete device.

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Figure 7 *The image shows a side view of the taper section. The outer diameter of the fiber is reduced from 600μm to 210μm over a 5mm section. (Note: The image is stitched together from several images due to the limited field-of*view of the applied microscope).*

In Figure 8, the measured attenuation of the 5 mm air-clad taper is shown. The test was performed by splicing a high-power connectorized standard multimode fiber cable onto the taper. The cable had a 400 µm core and 0.22 NA which is close to the parameters of the fused fiber bundle shown in Figure 3. This configuration allowed for a high power test of the taper not possible with the available pump diodes delivered in 105/125 fiber.

The test was performed to the maximum power of the used pump laser corresponding to almost 150W. Within the measurement uncertainty the measured attenuation was independent of transmitted power and in the order of 0.1 dB. No degradation from the high power levels was observed.

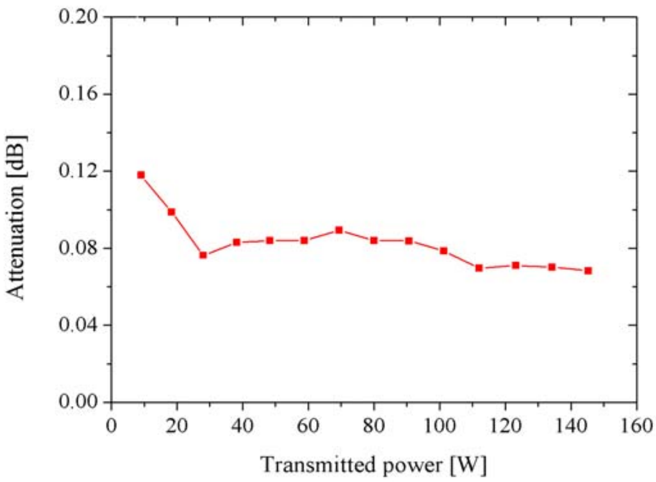

Figure 8 *The curve shows measured attenuation of the 5 mm long taper shown in Figure 5 and Figure 7 as function of transmitted power.*

CONCLUSION AND FUTURE WORK

Results from the development of a 7 port pump combiner based on 105/125 0.22 NA pump fibers have been reported. The main results are the realization of an un-tapered fused fiber bundle and a tapered air-clad PCF increasing the NA from 0.22 to 0.60. The taper was tested in a high power configuration showing no degradation and a transmission loss in the order of 0.1 dB.

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Remaining work includes the splicing of the fused fiber bundle to the input of the air-clad taper. The output of the taper can be spliced directly of a fiber laser subassembly or to a delivery fiber in the case where a stand-alone coupler is desired.

Finally, the section of uncoated input fibers, the fusing section, splice, taper, and output splice should be protected from mechanical damage by insertion into a glass or steel tube with stress relief on both in- and output.

I certify that there were no subject inventions to declare during the performance of this grant.

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